JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. D14, PAGES 16,741–16,753, JULY 27, 1999

Retrievals of vertical profiles of ice cloud microphysics from radar and IR measurements using tuned regressions between reflectivity and cloud parameters

Sergey Y. Matrosov

Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder
NOAA Environmental Technology Laboratory, Boulder, Colorado

Abstract. A new approach is suggested for retrieving vertical profiles of radiatively important microphysical parameters of ice clouds from measurements of radar reflectivity and estimates of cloud optical thickness. This approach is applicable to ground-based, vertical-mode measurements of pure ice phase clouds observed without blockage from low–liquid water clouds. It involves "tuning" the coefficient of the power law reflectivity–ice water content (Z_e-IWC) relations for each individual profile of radar measurements. This tuning is done based on the independent estimates of cloud ice water path obtained from layer-mean values of radar reflectivity and cloud optical thickness. After a vertical profile of IWC is retrieved using this approach, a corresponding vertical profile of cloud particle median sizes, D_m, can be easily calculated for an assumed type of the particle size distribution. By assuming that the exponent in the tuned Z_e-IWC relations changes linearly within a small dynamic range, better results are obtained compared with the case when it is assumed to be constant. The accuracy of the tuned regression approach is assessed by comparing the retrieval results for several high-quality observational cases with data from the "reference" method, which uses additional measurements of Doppler velocities. This method was verified by earlier comparisons with simultaneous in situ data. The specifics of using Doppler information, however, limit the applicability of this method and prevent its real-time applications. It is shown that the relative standard deviations of IWC and D_m retrievals using the tuned regression approach compared with the reference method are about 35% and 20%, respectively. These accuracies are much better than those that can be attained by any a priori chosen fixed regression between reflectivity and cloud microphysical parameters. At the same time, these accuracies are comparable to uncertainties of estimates of cloud parameters from direct in situ sampling. The suggested tuned regression approach is easy to implement and can be used for routine processing of ground-based, and, potentially, satellite-aircraft-based radar measurements of ice clouds.

1. Introduction

It is well recognized that ice clouds play a very important role in the Earth's radiation budget [e.g., *Stephens et al*., 1990]. The radiative properties of these clouds are largely determined by their microphysical parameters, such as ice water content (IWC) and characteristic cloud particle size. Monitoring these cloud parameters is required for better and more accurate representations of cloud effects in climate models. Only remote sensing approaches can provide such cloud data over long time periods at many locations.

A number of current and potential satellite techniques have been developed for retrieval of microphysical parameters of ice clouds [e.g., *Ou et al*., 1998; *Minnis et al*., 1995; *Han et al*., 1995; *Evans and Stephens*, 1995]. While the verification of such techniques remains an important problem, they have an obvious advantage in potential global coverage. Satellite techniques are based mostly on interpretation of multichannel radiometer measurements and hence can provide only vertically averaged information about clouds. Though vertically averaged parameters are very important, the vertical profiles of these parameters are essential for accurate representation of clouds in models. These profiles determine the vertical profile of the radiative heating/cooling rate of the atmosphere, which is considered to be one of the key elements of the cloud-climate feedback [*Ramanathan and Collins*, 1991].

Active remote sensors such as radars and lidars are the obvious choice for providing vertically resolved information on clouds. Relatively strong attenuation of visible and IR signals in clouds, however, limits the applicability of lidars, though lidars are very helpful for remote sensing of thin clouds, especially in combination with other remote sensors [e.g., *Intrieri et al*., 1993; *Platt and Dilley*, 1981]. Millimeter-wavelength radars also proved to be a very powerful tool for studying nonprecipitating clouds and especially high-altitude ice clouds such as cirrus.

During the last decade, a number of 35-GHz (Ka band) and 94-GHz (W band) radars have been developed and used extensively for studies of ice clouds [e.g., *Matrosov et al*., 1992; *Kropfli et al*., 1995; *Clothiaux et al*., 1995; *Sekelsky and McIntosh*, 1996; *Kropfli and Kelly*, 1996; *Mace et al*., 1997; *Moran et al*., 1998]. Most of this research is being done with ground-based measurements. However, airborne W-band radars have been also successfully used by the universities of Massachusetts and Wyoming [e.g., *Galloway et al*., 1997]. A W-band satellite

Paper number 1999JD900244.
0148-0227/99/1999JD900244$09.00

radar mission is currently being planned [*International GEWEX Project Office*, 1994], and a spaceborne cloud radar may be launched in a few years.

The basic radar measurable, equivalent radar reflectivity Z_e, alone, is not sufficient for retrieval of any microphysical property of clouds, so multisensor approaches are being developed for such retrievals. A method that uses measurements of radar reflectivity and IR brightness was suggested by *Matrosov et al*. [1992] for retrievals of vertically averaged ice cloud particle characteristic size and ice water path (IWP), the vertical integral of IWC. This approach was substantially modified for use with interferometer data [*Mace et al*., 1998] and is being used now for routine retrievals of layer-mean values of ice cloud microphysics at the Atmospheric Radiation Program (ARM) experimental sites.

Retrievals of vertical profiles of cloud parameters require additional measurements. *Sekelsky et al*. [1999] suggested a multifrequency (3,35, and 94 GHz) approach for retrieving microphysical profiles. This approach, however, is probably restricted to clouds with a very large characteristic size of cloud particles because of the Rayleigh-type scattering at all three frequencies for smaller particles. The method suggested by *Matrosov et al*. [1994] uses vertical Doppler velocity measurements in addition to Z_e and IR measurements to retrieve vertical profiles of IWC and characteristic particle size. Though this method proved to be successful for individual ice cloud case studies [*Matrosov*, 1997; *Matrosov et al*., 1998], it has some limitations due to specifics of the Doppler information (e.g., requirements for low turbulence and small air vertical motions in cloud). These limitations and the required temporal averaging make this method inconvenient for the routine real-time retrieval of cloud parameters.

The simplest way to estimate vertical profiles of the desired cloud parameters is to use two-parameter relations or, as they are sometimes called, regressions between radar reflectivity Z_e and a cloud microphysical parameter of interest. The latter are usually based on the power law form and are analogous to the Z_e-R relations for measuring rainfall rate R. They are convenient to implement in real-time processing. These properties make such regressions a tempting choice for long-term continuous data sets such as those from potential satellite radar. Nevertheless, the accuracies of single-parameter relations are generally inadequate because cloud particle size distributions are multiparameter in their nature.

In this paper, an approach is proposed for "tuning" two-parameter regressions. Such tuning is made for each profile of radar reflectivity data based on an independent estimate of cloud optical thickness. This approach provides a much better accuracy than any a priori regression. At the same time, it is versatile and can be efficiently used for real-time processing of radar data.

2. Radar Reflectivity As a Function of Ice Cloud Parameters

Equivalent radar reflectivity factor (hereinafter referred to as reflectivity for brevity) Z_e is the principal radar measurable. *Atlas et al*. [1995] showed that

$$Z_e = GD_m^3\mathrm{IWC}, \tag{1}$$

where D_m is some characteristic particle size in terms of the diameter of the equal-volume sphere and the coefficient G depends on particle shape, bulk density ρ, and the details of the particle size distribution (PSD). Usually, the gamma functions satisfactorily describe particle size spectra in ice clouds [*Kosarev and Mazin*, 1991], and, in this case, G dependence on PSD is reduced to the dependence of the order of the gamma PSD, n: $G = G(\rho, n, r)$, where r is a shape parameter (e.g., particle aspect ratio).

In many satellite remote sensing methods based on passive measurements, it is assumed that the density of ice cloud particles is constant. It has been shown, however [e.g., *Heymsfield*, 1972], that only relatively small cloud particles can be assumed to be made of solid ice. The effective bulk density ρ of larger particles reduces with the increase of particle size D. *Brown and Francis* [1995] showed that the effective bulk density of ice cloud particles greater than about 100 μm can be approximated by

$$\rho(\mathrm{g\ cm^{-3}}) \approx 0.071D^{-1.1} \tag{2}$$

Here D is an average of dimensions in millimeters measured by a standard two-dimensional (2-D) aircraft probe. Conversions between 2-D probe sizes and equal-volume spherical diameters were discussed by *Matrosov et al*. [1995].

With the assumed relation (2), the coefficient G in (1) will depend on characteristic particle size as a proxy of its density dependence. Figure 1 shows modeled values of G as a function of D_m (hereinafter we will use cloud particle median volume size D_m as a characteristic size describing the whole PSD). The units of the coefficient G are such that IWC is in g m^{-3}, D_m is in microns, and Z_e is in mm^6 m^{-3}. Nonspherical ice cloud particles were modeled as oblate and prolate spheroids, with larger dimensions distributed randomly in the horizontal plane.

Since the dependence on D_m in Figure 1 is a substitute for the density dependence, the mean mass-weighted density ρ_0 was calculated as a function of D_m:

$$\rho_0(D_m) = \frac{\int_0^\infty \rho(D)\, D^3 N(D, D_m, n) dD}{\int_0^\infty D^3 N(D, D_m, n)\ dD} \tag{3}$$

where N is the gamma-function size distribution: $N(D, D_m, n) = N_0 D^n \exp(-(3.67 + n)D/D_m)$. Figure 2 shows ρ_0 as a function of D_m for the first 3 orders of the gamma distribution.

It can be seen from Figure 1 that G is diminishing with particle characteristic size. The relatively rapid decrease of G for D_m greater than about 50–60 μm is associated with a decrease in particle bulk density, which reduces radar reflectivity. Even after accounting for density changes, the variability of G is generally within 1 order of magnitude for most of the D_m dynamic range.

A natural variability of IWC in upper tropospheric ice clouds is about 3 or 4 orders of magnitude [*Dowling and Radke*, 1990; *Matrosov*, 1997]. Typical values of particle median size that could be retrieved with the help of cloud radar with typical sensitivity (about -30 dBZ at 10-km range) are 30–400 μm. Sizes of individual particles vary over a greater dynamic range. From these variability assessments and (1), one can see that characteristic cloud particle size and IWC contribute about equally in variability of radar reflectivity, i.e., 3 or 4 orders of magnitude. For larger particle sizes the decrease of the particle

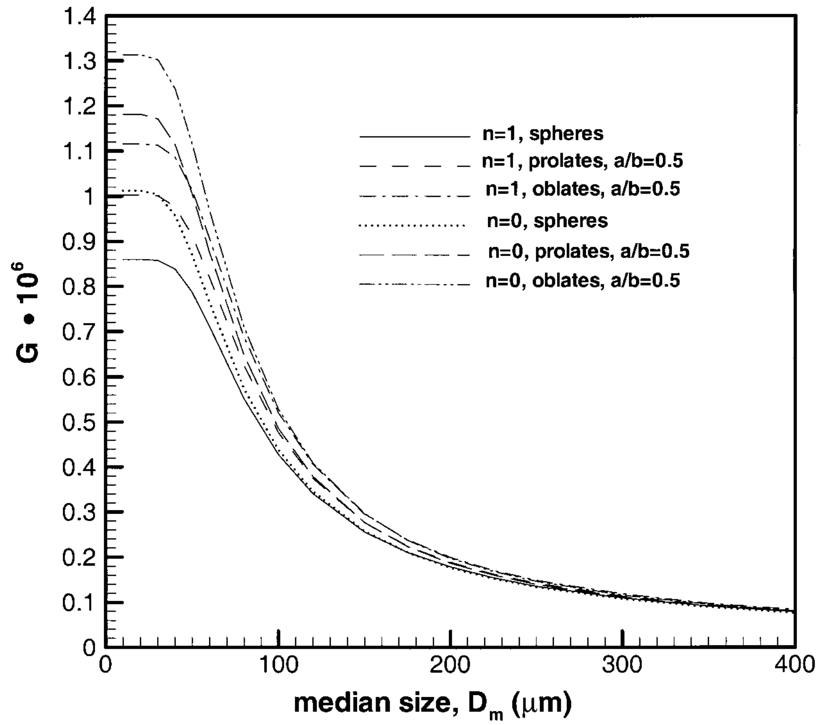


Figure 1. Coefficient G as a function of particle median size D_m for different orders of the assumed Gamma-function particle size distributions n and different particle aspect ratios r.

bulk density effectively reduces the variability of Z_e due to changes in D_m. The variability of Z_e due to other factors is much smaller.

Atlas et al. [1995], for example, estimated the variability of G due to changes in n from 0 to 2, which cover an adequate interval of this parameter according to the experimental work by *Kosarev and Mazin* [1991]. G decreases slightly when n increases. This variability of G, however, was found not to

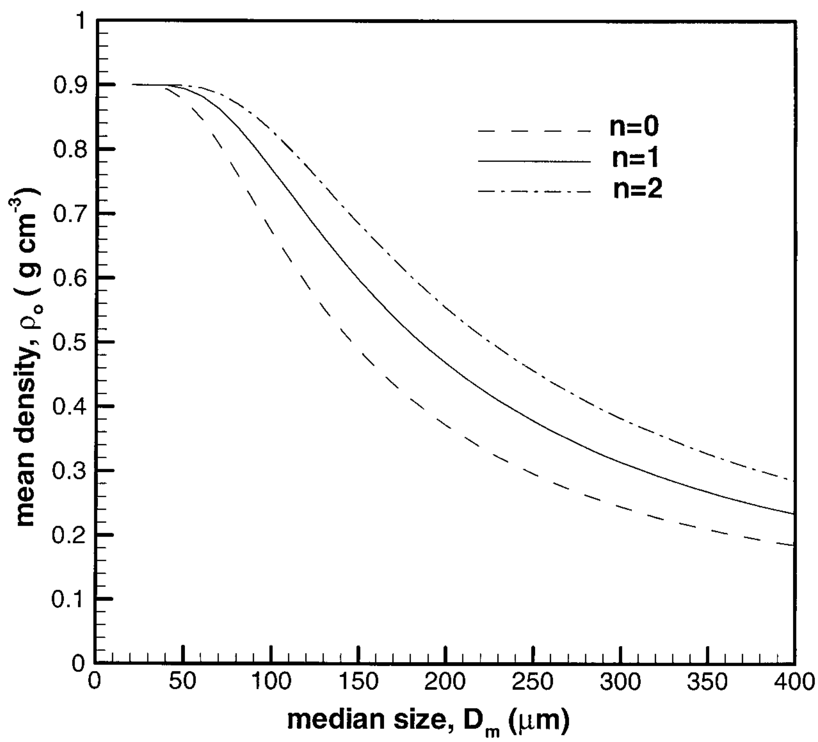


Figure 2. Mean density ρ_0 as a function of the median particle size D_m for different orders n of the gamma particle size distribution assuming that individual particle bulk density is given by equation (2).

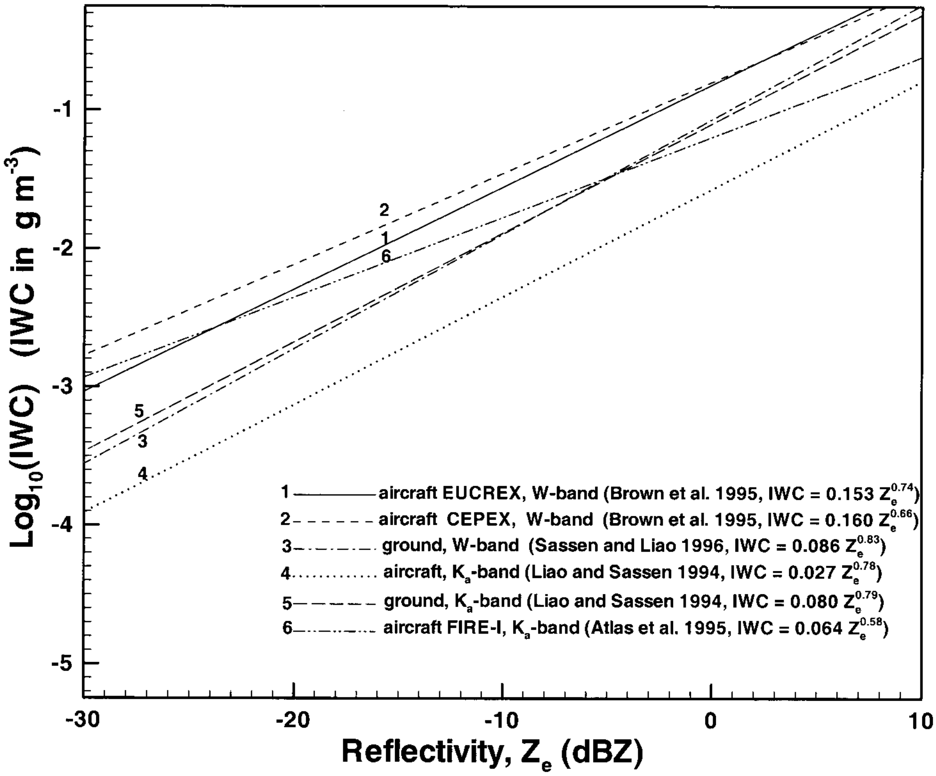


Figure 3. Empirical Z_e-IWC regressions from different studies.

exceed about 15% relative to the value in the middle of this interval (i.e., $n = 1$). As can be seen from Figure 1, the variability of G decreases as D_m increases. The larger particles become optically "softer" due to the decrease in the bulk density and shape, and PSD details become less significant.

All of the above mentioned means that radar reflectivity can be approximately considered as a function of just two cloud parameters; the contributions from all other factors are of secondary importance. Note that the choice of these two principal cloud parameters can be different (e.g., characteristic particle size and total particle concentration, C, or IWC and C). Here we consider a pair, D_m and IWC, mainly because of the convenience and importance of these parameters to understanding the radiative properties of ice clouds.

3. Empirical Z_e-IWC Regressions

3.1. Experimental Z_e-IWC Regressions

A considerable number of studies have been devoted to deriving Z_e-IWC regressions. These regressions are usually obtained empirically from cloud samples when both Z_e and IWC are calculated from these samples simultaneously. The main problem with such an approach, as can be seen from (1) and the analysis given in the previous section, is that radar reflectivity is not related to IWC in a one-to-one fashion.

Nevertheless, a significant correlation between Z_e and IWC exists which allows constructing power law regressions:

$$\mathrm{IWC} = aZ_e^b. \quad (4)$$

As can be seen from (1), for a constant particle characteristic size, $b = 1$ and the coefficient a depends primarily on D_m. A nice experimental illustration of Z_e-IWC relations for constant values of D_m is given by *Atlas et al.* [1995]. Variability of particle characteristic sizes in samples used to derive regressions results in the exponent b being smaller than 1.

Figure 3 shows several experimental Z_e-IWC regressions found in recent publications. These regressions were derived from particle samples taken from aircraft or at the ground. Note that the regressions depicted in this figure were obtained for two different millimeter radar wavelength bands: W ($\lambda \sim 3$ mm) and Ka ($\lambda \sim 8$ mm). This wavelength difference, however, is not a reason for significant variation of these regressions because particles in nonprecipitating ice clouds are generally within limits of the Rayleigh-type scattering for both considered radar bands. Comparisons of regressions 3 and 5 illustrate this statement. These two regressions are very close. They were derived from the same data set but for different radar wavelength bands.

The variability of the experimental Z_e-IWC regressions shown in Figure 3 is mostly due to the variability of characteristic particle sizes in samples used for derivations of these regressions. In the two extreme cases (regressions 2 and 4), values of IWC calculated for the same value of radar reflectivity can differ by as much as 1 order of magnitude. All this shows that an application of any a priori chosen, experimental Z_e-IWC regression for retrievals of ice cloud content from different experimental cases could result in substantial retrieval errors.

3.2. Z_e-IWC Regressions Derived From Multisensor Measurements

More robust methods to retrieve cloud microphysical parameters must make use of other measurements in addition to radar reflectivity data. It can be seen from (1) that an addi-

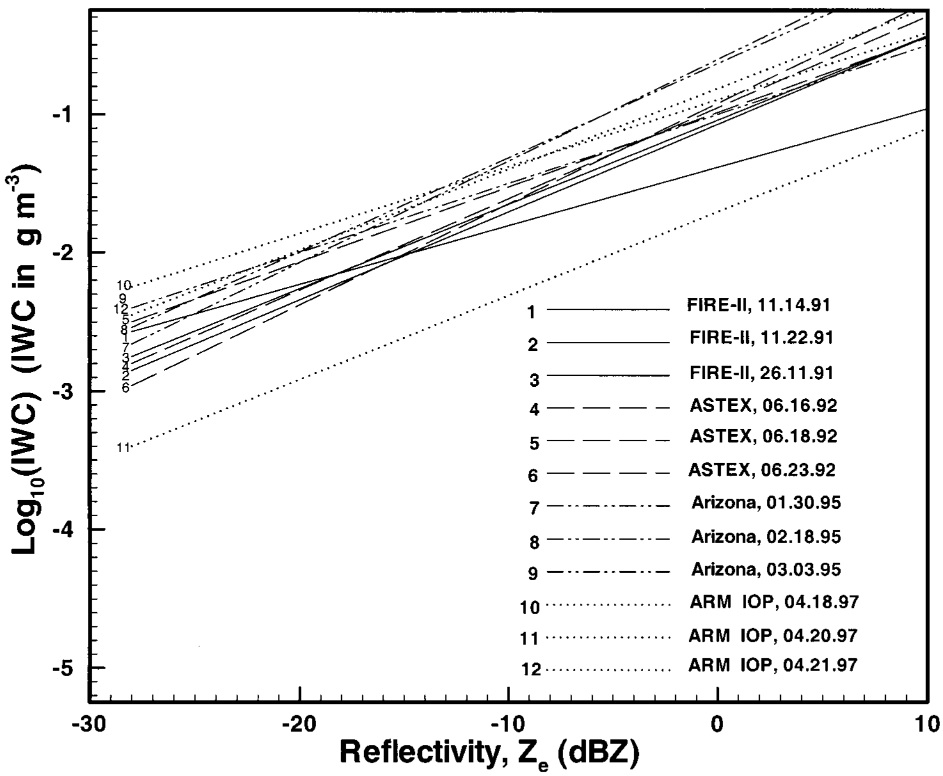


Figure 4. Z_e-IWC regressions from 12 observational ice cloud cases retrieved with multisensor measurements.

tional vertical profile of independent data is generally needed to resolve an ambiguity between contributions of D_m and IWC to radar reflectivity. As was indicated by *Atlas et al.* [1995], the ambient temperature cannot be used to reliably parameterize cloud particle characteristic size.

The ice cloud profile retrieval method suggested by *Matrosov et al.* [1994] and further developed by *Matrosov* [1997] uses IR brightness and vertical profiles of Doppler velocity in addition to reflectivity measurements to obtain vertical profiles of D_m and IWC independently. The IR measurements are essential to this method because the particle vertical velocities estimated from Doppler information are difficult to interpret due to the lack of a well-defined and universal relationship between ice cloud particle fall velocities and their sizes. IR measurements are used to estimate cloud optical thicknesses that, in turn, are used to normalize vertical profiles of cloud absorption coefficient. Note these estimates are available for the range of absorption optical thickness from about 0.03 to 3.5. The vertical profile of the absorption coefficient is calculated at each step of an iterative retrieval procedure from vertical profiles of D_m and IWC. This method will be referred to hereinafter as the full radar–radiometer method.

The full radar–radiometer method uses the procedure of averaging vertical Doppler measurements [*Orr and Kropfli*, 1999] to get estimates of particle fall velocities. This procedure requires the absence of strong updraft/downdraft motions in cloud and low turbulent activity. Estimations of instantaneous profiles of particle fall velocities for each beam of radar data can be done only a posteriori after several hours of observations. For this purpose, the averaged Doppler information is used to construct regressions between Z_e and residual Doppler velocities for different cloud altitudes. The requirement of a posteriori averaging prevents one from using this method for real-time data processing.

The full radar–radiometer method, however, is very useful for cloud case studies and proved to be rather efficient for several hour-long observations of ice clouds which met the requirements mentioned above. Microphysical retrievals using this method were performed for a significant number of ice cloud cases observed during various experimental field programs with the NOAA Environmental Technology Laboratory (ETL) ground-based transportable Doppler Ka-band radar (λ = 0.86 cm) [*Kropfli et al.*, 1995] and the narrowband IR radiometer ($\lambda \sim$ 10–11.4 μm).

One important point when using several remote sensors is matching their resolutions. The ETL Ka-band radar and IR radiometer have 0.5° and 2° angular beam widths, respectively. For a typical cloud height of 7.5 km, these beam widths correspond to 65 and 260 m, respectively. This discrepancy, however, is mitigated by the fact that measurements used for retrievals represent 30-s averages. During the averaging time the cloud advects at approximately 750 m (at typical horizontal winds of 25 m s^{-1} at such heights). This scale is greater than both radar and radiometer instantaneous horizontal resolutions. Hence the retrieval results represent average cloud microphysics over this horizontal scale.

Figure 4 shows Z_e-IWC regressions for some representative observational cases of high-tropospheric ice clouds. These specific case-dependent regressions were derived from measured values of Z_e and retrieved values of IWC for cloud samples with 30-s and 37.5-m temporal and vertical resolutions. The presented cases were observed during four recent cloud field programs in which ETL participated with its instrumentation. These field programs include the First International Satellite

Cloud Climatology Project (ISCCP) Regional Experiment, Phase II (FIRE-II) at Coffeyville, Kansas, in 1991; the 1992 Atlantic Stratocumulus Transition Experiment (ASTEX) in Porto Santo, Madeira, Portugal; the 1995 Arizona Program in Cottonwood, Arizona; and the 1997 Intensive Operation Period (IOP) at the southern Great Plains (SGP) cloud and radiation test bed (CART) site of the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program.

Unlike the regressions in Figure 3, where both IWC and Z_e are obtained from 2-D Particle Measuring System (PMS) cloud samples, the regressions in Figure 4 are obtained from radar measurements of Z_e and IWC values retrieved using the full radar–radiometer method. It can be seen from comparing Figures 3 and 4 that Z_e-IWC regressions derived both empirically and from the remote sensing method occupy approximately the same area in the Z_e-IWC plane except for very low reflectivities ($Z_e < -20$ dBZ), where measurements are usually less reliable. This consistent result illustrates the variability of Z_e-IWC regressions from case to case and quantitatively and qualitatively underlines the intrinsic uncertainty of these regressions.

4. Tuned Z_e-IWC Regressions

Values of a and b are not known a priori for any particular cloud. However, an examination of the Z_e-IWC regressions shown in Figures 3 and 4 shows that the coefficient a varies greatly, while the exponent b is usually between 0.6 and 0.7. This suggests the possibility of "tuning" the coefficient a on a profile-to-profile basis if some value of b is assumed a priori (e.g., $b = 0.65$). Such tuning can be done if the vertical integral of IWC-IWP is known independently for each beam of radar reflectivity data:

$$a = \mathrm{IWP} \Big/ \int [Z_e(h)]^b \, dh, \tag{5}$$

where the integration is carried out from the cloud base to the cloud top.

The IWP values that are necessary for tuning can be obtained from the layer-mean radar reflectivity and IR estimates of cloud optical thickness as suggested in the method described by *Matrosov et al*. [1992]. This method is an abbreviated version of the full radar–radiometer method for microphysical profiles. Because it does not use Doppler information, it is not subject to the above mentioned limitations due to the use of this information.

The tuning procedure offers a Z_e-IWC relationship specifically tailored for each vertical profile of radar measurements. On average, this procedure should allow retrieving vertical profiles of IWC with much better accuracy than those attainable using a priori Z_e-IWC relationships with fixed values of a and b. On the other hand, the accuracy of IWC retrievals using the tuning approach would not be as good as one for the full radar–radiometer method. The advantage of this approach is in its versatility and the possibility of real-time processing of radar measurements. The potential sacrifice in retrieval accuracy can be estimated by comparisons with the results of the full method.

In some respect, this approach has similarities with the approach for profiling liquid water content (LWC) in warm stratus clouds [*Frisch et al*., 1998]. In the latter one, however, the direct estimates of the LWC vertical integral are readily available from microwave radiometer measurements. The approach suggested here uses more statistical information about the type of reflectivity–cloud content relations and does not make assumptions about particle concentration.

4.1. "Tuned" Z_e-IWC Regressions With Fixed Value of the Exponent b

Illustrations of tuning coefficient a in Z_e-IWC regressions are given in Figures 5 and 6. Two ice cloud cases from those mentioned in Figure 4 are chosen here for these illustrations. The FIRE-II November 26, 1991, cirrus priority case included observations by a large suite of ground-based instrumentation in addition to simultaneous in situ sampling taken by three research aircraft. During this case an ice cloud evolving from a very thin cirrus to a very thick (about 3.5 km) cloud with a base at about 5.5 km was observed during the 3-hour period [*Intrieri et al*., 1995]. The case of June 23, 1992, from ASTEX was characterized by a relatively steady cirrus cloud located mostly between 6 and 9 km.

When calculating a value of the coefficient a for each vertical profile of radar data, it was assumed that the exponent $b = 0.65$. Each vertical profile of radar data represented 30-s averages of reflectivity measurements. The data gaps in Figures 5 and 6 are due to radar scanning measurements off vertical (e.g., 6 min at the end of each half-hour interval) or patches of lower-altitude liquid cloud between the ground and the ice cloud (e.g., 15-min interval after 2000 UTC for the FIRE-II case).

It can be seen from (1) that a should decrease with the increase of characteristic particle size. It is clearly seen for the November 26 FIRE-II case, where the general trend of increase in the layer-averaged particle median size (Figure 5b) results in the general decrease of a. Values of a are generally between 0.25 and 0.05 for this case, which is in general agreement with this coefficient's variability in the empirical regressions shown in Figure 3. The parameters of the Z_e-IWC regression constructed from the multisensor measurements for this case are $a \approx 0.093$ and $b \approx 0.60$. Note that this a value is closer to the lower limit in Figure 5a because of the large number of cloud samples from 2030 to 2130 UTC due to geometrical thickness of the cloud during this period.

For most of the June 23, 1992, ASTEX case shown in Figure 6, median particle sizes did not show much variability (except for the last 10 min). This resulted in a relatively low variability of the coefficient a. The regression derived from multisensor measurements for this whole case was IWC $\approx 0.120 Z_e^{0.73}$. Note that this regression is relatively close to the empirical one derived by *Brown et al*. [1995] based on aircraft microphysical sampling during European Cloud Radiation Experiment (EUCREX).

4.2. Tuned Z_e-IWC Regressions With Changeable Value of the Exponent b

It can be shown [*Atlas et al*., 1995] that the deviation of the exponent b from 1 in Z_e-IWC regressions is related to the variability of characteristic particle size in the cloud samples (from either in situ or remote measurements) used for deriving this regression. The greater variability of D_m generally results in smaller values of b.

Multisensor retrievals of ice cloud microphysics indicate that for a typical vertical profile of D_m, the smallest particle sizes are observed near the cloud top. D_m then usually increases at a progressively slower rate until it reaches maximum values not far from the cloud base. The rapid sublimation occurs in the

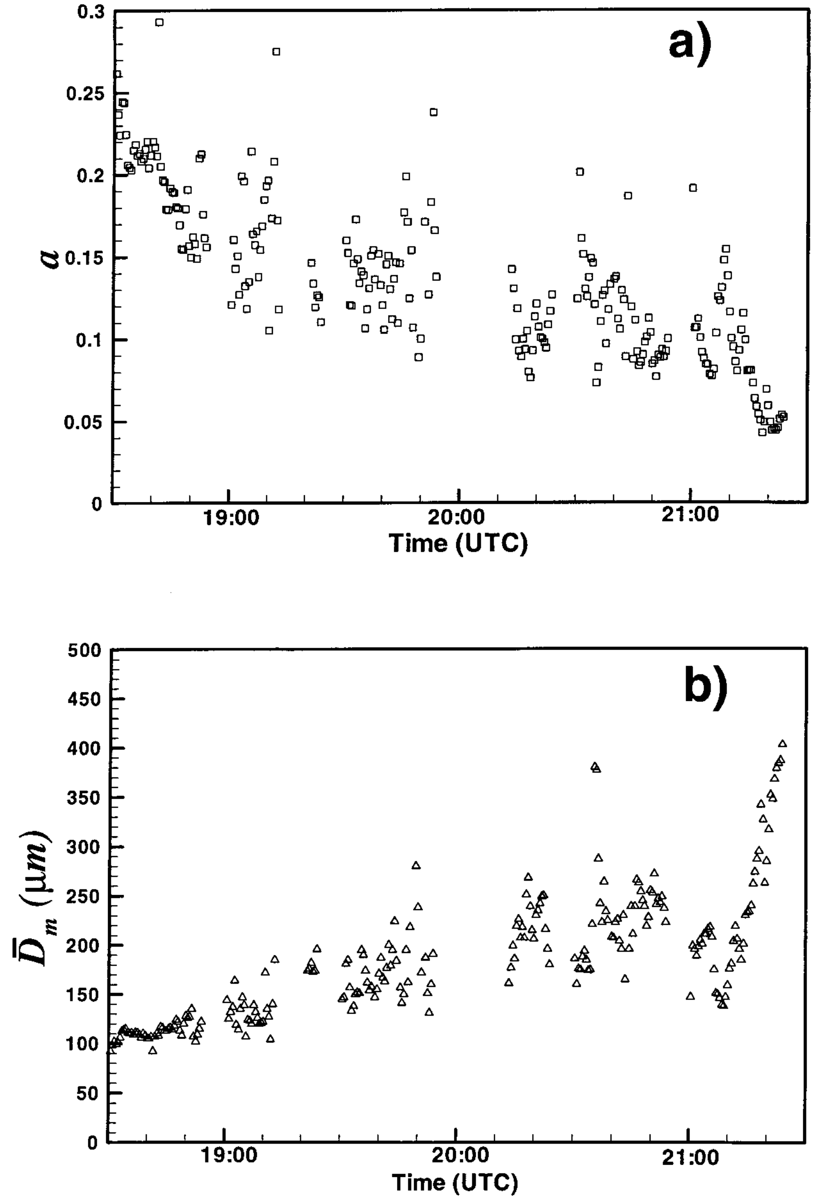


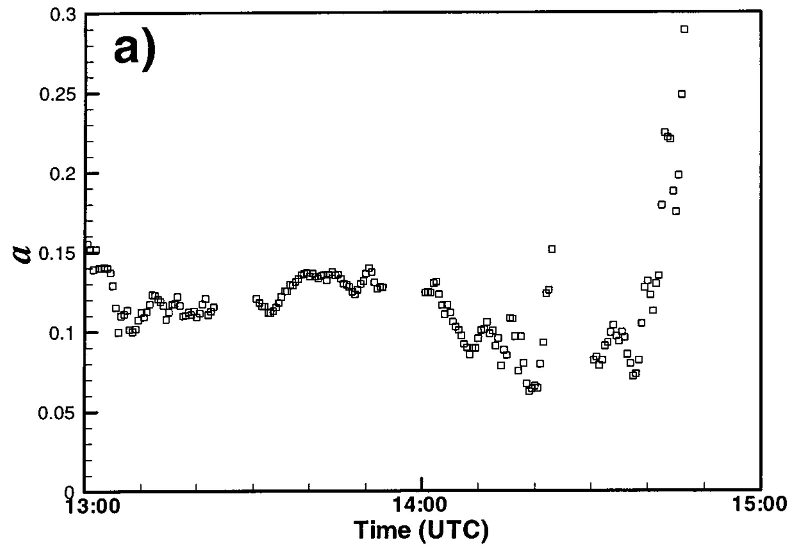
Figure 5. Coefficient a in a tuned Z_e-IWC regression with (a) $b = 0.65$ and (b) the layer-averaged particle median mass size as a function of time for the ice cloud observed on November 26, 1991. The units of a are such that IWC is g m^{-3} and Z_e is in mm^6 m^{-3}.

nearest vicinity of the cloud base. The statistics of D_m vertical profiles retrieved using the full radar–radiometer method [*Matrosov*, 1997] show that, in general, the variability of D_m values in the upper part of the cloud is higher than in its lower part. This indicates that values of the exponent b in the upper cloud parts should be smaller than in the lower parts.

The vertical variability of the exponent b is illustrated in Figure 7. Figure 7a shows the correspondence of IWC values retrieved with the full radar–radiometer method and measured radar reflectivity for one profile observed during the ASTEX case of June 23, 1992. This vertical behavior of the IWC-Z_e correspondence is quite typical for many retrieved profiles. It can be seen that the slope of the best power law fit (i.e., the exponent b) for the upper part of the cloud between about 8.3 and 7.1 km is smaller than the slope for the lower part of the cloud. Note that this "hysteresis"-like effect was also obtained through cirrus modeling [*Sassen and Khvorostyanov*, 1998].

Figure 7b shows two Z_e-IWC regressions derived for the whole case of June 23, 1992, but for different cloud altitudes. The first regression (IWC $= 0.105Z_e^{0.60}$) was derived from cloud samples located in the upper half of the cloud between 7.5 and 9 km. In contrast, when cloud samples from the lower part of the cloud (between 6 and 7.5 km) were taken into account, the regression IWC $0.132Z_e^{0.83}$ resulted. Note that qualitatively, the results of Figure 7 are repeatable for other observational cases listed in Figure 4.

The discussion given above suggests that a tuned regression with changeable value of the exponent b could be a more reasonable choice than the one with constant value of b. Equation (5) can still be used to calculate a for each vertical beam



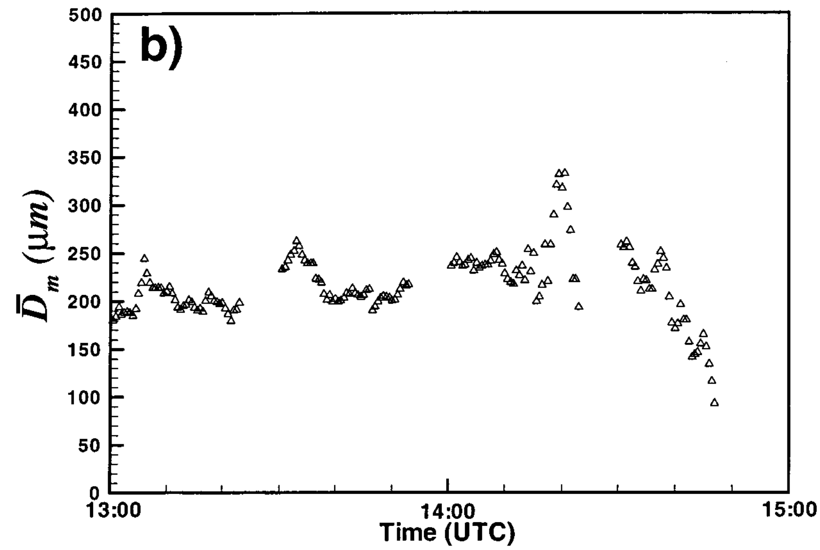


Figure 6. Same as in Figure 5 but for the ice cloud observed on June 23, 1992.

of radar data, but b in this case should depend on altitude within the cloud. The simplest assumption about this dependence is a linear change of b with height from $b_{\min}$ at the cloud top to $b_{\max}$ at the cloud base. The optimal choice of $b_{\max}$ and $b_{\min}$ and relative accuracy of tuned regressions with fixed and changeable exponents can be estimated by comparing retrieved IWC profiles with reference values.

4.3. Accuracy of the Tuned Regression Approach

The accuracy of the Z_e-IWC regressions was estimated taking into account all the observational ice cloud cases mentioned in Figure 4 under the assumption that the results obtained with the full radar–radiometer method (with the use of the Doppler measurements) are true. These results were used as reference values. This assumption is supported by the good agreement between the full-method retrieval results and the in situ data obtained by instrumented aircraft [*Matrosov et al.*, 1998]. The in situ data themselves cannot be used comprehensively here because they are available only for a limited number of aircraft passes during two experimental cases mentioned above (November 26, 1991, and April 18, 1997). The approach used here to determine the accuracy of tuned regressions is rather convenient because the temporal and spatial resolutions of the full-method retrievals are the same as for regressions. Furthermore, such accuracy estimations can be done for the data sets consisting of thousands of cloud samples.

On the basis of the discussion given above, a relative standard deviation (RSD) between the IWC values obtained using Z_e-IWC regressions and the ones from the full radar–radiometer method was used as an estimator of the accuracy of different regression approaches. Table 1 presents RSD values for different regressions. These values represent an average for the 12 ice cloud observational cases listed in Figure 4. More than 140,000 cloud samples (each sample representing a 30-s time average and 37.5 m of the cloud vertical resolution) were used to generate the average RSD values given in Table 1.

The first row in Table 1 presents an average RSD for the situation when for each particular observational case, the re-

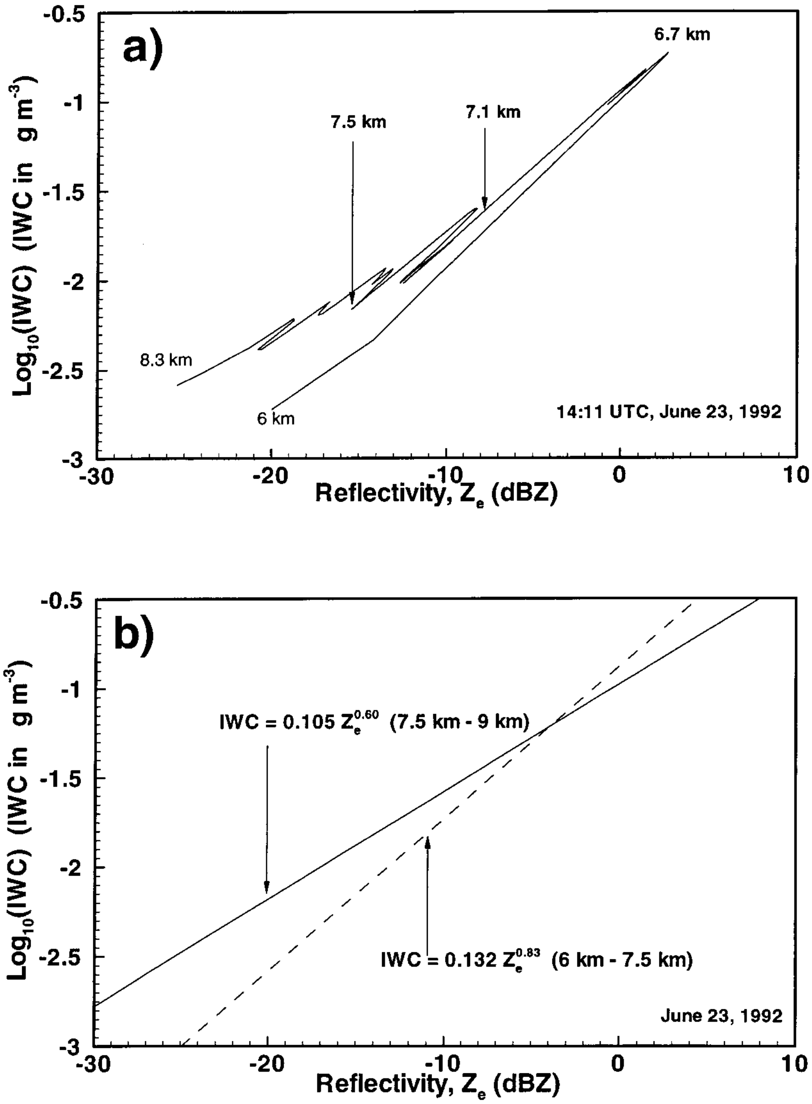


Figure 7. (a) Measured radar reflectivity versus IWC retrieved from multisensor measurements for one vertical profile of data at 1411 UTC on June 23, 1992. (b) Z_e-IWC regressions for the whole observational case (solid line is for the upper part of the cloud, and the dashed line is for the lower part of the cloud).

gression specifically derived for this entire case was used (see Figure 4). The next three rows represent average RSD values for the empirical regressions 5, 4, and 2 given in Figure 3, which are the middle, the lowest, and the highest regression lines in this figure. As one can see, the accuracy of the empirical regressions is always less than the accuracy of the case-dependent regression (row 1), indicating that the regression drawn specifically for a particular case works better in most situations than any a priori–chosen regression derived from a different data set. The specific case-dependent regression, however, cannot be known a priori. Note that RSD values close to 100% for regression 4 mean almost 1 order of magnitude underestimation in IWC values calculated from this regression because RSD ~ ($IWC_{reg}-IWC_{ref}$)/IWC_{ref}, where IWC_{reg} and IWC_{ref} mean values derived from the regression approach and the full radar–radiometer reference method, respectively.

Table 1. Average Relative Standard Deviations of Power Law Regressions (IWC = aZ_e^b)

	Relative Standard Deviation, %
Case-dependent regression	56
"Middle" regression (5)	78
"Low" regression (4)	95
"High" regression (2)	75
"Tuned" regression (b_{min} = 0.65)	45
Tuned regression (b_{min} = 0.60, b_{max} = 0.70)	34
Tuned regression (b_{min} = 0.55, b_{max} = 0.75)	35
Tuned regression (b_{min} = 0.50, b_{max} = 0.80)	38

The average RSD value for the tuned regression with a fixed value of the exponent b (fifth row) provides a significant improvement over any of the regressions with fixed parameters. Tuned regressions with a changeable value of b demonstrate even further accuracy improvement. Note that RSD values do not change much for different combinations of b_{min} and b_{max} listed in rows 6–8 in Table 1. In general, tuned regressions with changeable values of b provide an accuracy improvement of more than a factor of 2 (in relative terms) compared with fixed empirical regressions. A relative accuracy of about 35% of the

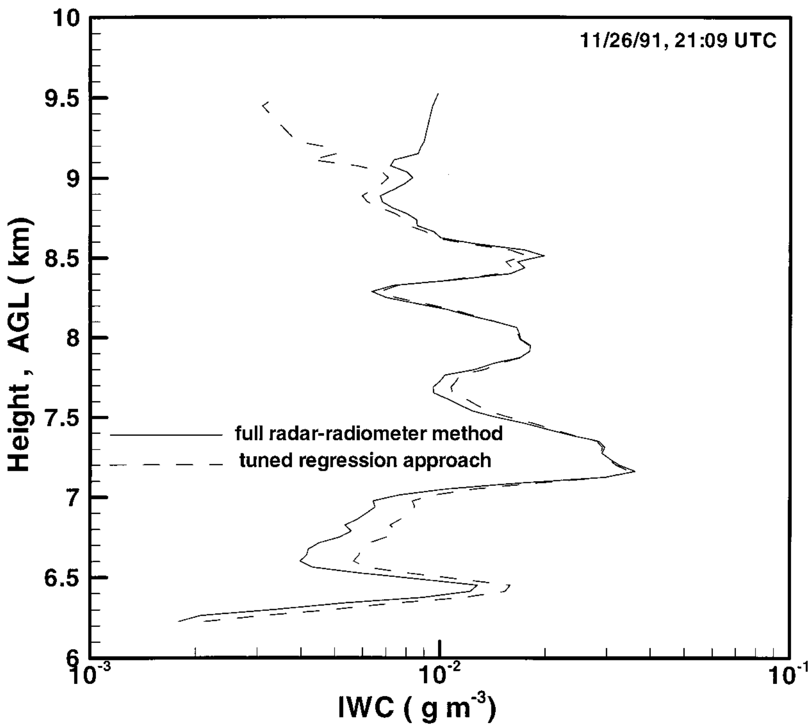


Figure 8. An example of IWC retrievals using the full-radar radiometer method and the "tuning" approach, with $b_{\min} = 0.6$ and $b_{\max} = 0.7$.

tuned regression approach should be considered quite satisfactory given several orders of magnitude of IWC variations in observed clouds.

Figure 8 shows an example of IWC vertical profile retrievals from the full radar–radiometer method and from the tuned Z_e-IWC regression with $b_{\min} = 0.6$ and $b_{\max} = 0.7$. This example is from the FIRE-II cirrus priority case (November 26, 1991) for the approximate time of the satellite pass (2109 UTC). It can be seen from Figure 8 that the agreement between IWC values retrieved using both methods is quite good except for some discrepancies near the cloud top. The RSD value of the tuned regression estimates for this observational case was 25%, which is noticeably smaller than an average RSD for this type of regression (35%). It should be mentioned here also that the accuracy of the full radar–radiometer method generally degrades in the vicinity of cloud tops because Doppler velocities usually observed there are quite small and their measurement accuracy is not as good as for greater velocities observed for larger, faster falling particles.

5. Retrievals of Particle Median Size Profiles Using the Tuned Regression Approach

An independent regression approach, based on power law Z_e-D_m relations, can be used to derive particle median size from radar reflectivity measurements. Such relations for a number of experimental ice cloud cases were considered by *Matrosov* [1997]. It should be mentioned, however, that IWC and D_m derived independently from different regression approaches could provide conflicting values which would not satisfy the basic equation (equation (1)). A more robust way to estimate vertical profiles of D_m is to do so based on (1) if IWC profiles are derived using the procedures discussed in the previous section.

Whenever a vertical profile of IWC is retrieved for a particular vertical profile of radar reflectivity data using a tuned regression approach, a profile of cirrus particle median sizes can be directly calculated from (1). With no independent a priori information on these cloud particle properties, the following approximation can be suggested for the coefficient G as a function of particle median size:

$$G(D_m) \approx 0.74 \times 10^{-4} D_m^{-1.1} \qquad (D_m \geq 50\ \mu\text{m}).$$
$$G(D_m) \approx 10^{-6} \qquad (D_m < 50\ \mu\text{m}). \tag{6}$$

This approximation represents an average $G(D_m)$ dependence from Figure 1. The units of G, as before, are such that Z_e, D_m, and IWC in (1) are in mm^6 m^{-3}, μm, and g m^{-3}, respectively.

As with the IWC retrieval accuracy considered in section 4.3, the accuracy of retrieving vertical profiles of D_m was estimated considering the retrieval results with the full radar–radiometer method as reference values. This estimation was also performed for the same ice cloud retrieval cases listed in Figure 4. Table 2 presents RSD values of median size retrievals for

Table 2. Average Relative Standard Deviations of Particle Median Size Retrievals

	Relative Standard Deviation, %
Case-dependent regression	34
"Middle" regression (5)	98
"Low" regression (4)	199
"High" regression (2)	48
"Tuned" regression ($b = 0.65$)	23
Tuned regression ($b_{\min} = 0.60$, $b_{\max} = 0.70$)	18
Tuned regression ($b_{\min} = 0.55$, $b_{\max} = 0.75$)	19
Tuned regression ($b_{\min} = 0.50$, $b_{\max} = 0.80$)	21

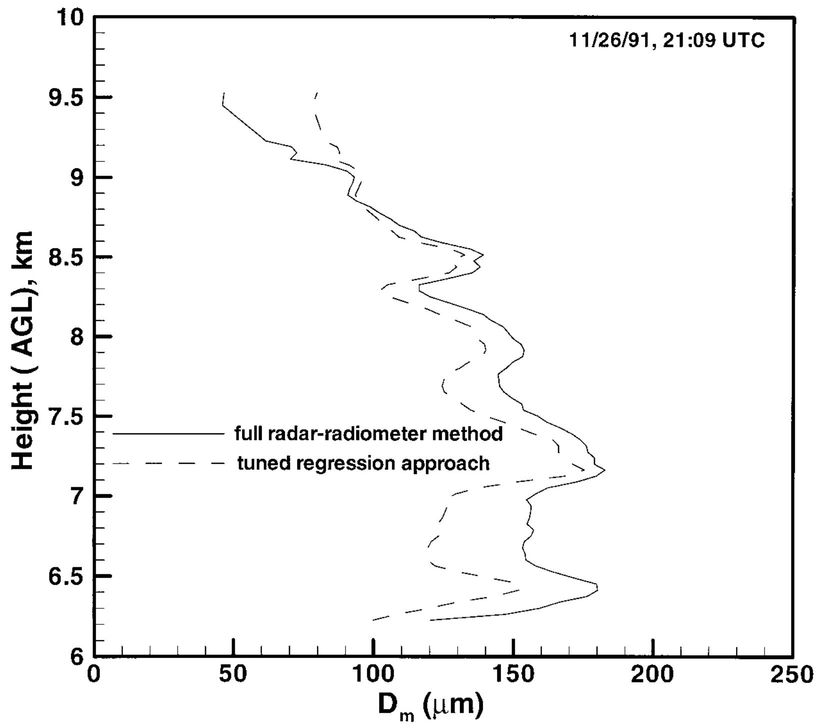


Figure 9. Same as in Figure 8 but for the retrievals of median particle sizes D_m.

different regressions used to estimate IWC. The meaning of the rows in Table 2 is the same as in Table 1.

It can be seen from Table 2 that the case-dependent regression (row 1), which is not known a priori, provides the best accuracy from "fixed" regressions (rows 2–4). A decent accuracy of particle size retrievals is also provided when the Central Equatorial Pacific Experiment (CEPEX) Z_e-IWC empirical regression derived by *Brown et al.* [1995] (row 4) is used. This is probably due to the similarity of microphysical conditions in the ice cloud cases considered here and those of the CEPEX data set.

The empirical regression IWC = $0.027Z_e^{0.78}$ (regression 4 in Figure 3) provides the lowest IWC values for given values of Z_e. As a result, particle median sizes D_m obtained from (1) (when IWC is estimated from this regression) are significantly larger than those obtained from the full radar–radiometer method. This results in large values of corresponding relative standard deviations (see row 3 in Table 2).

As in the case of IWC, the tuned regression approach provides a significant improvement in the accuracies of particle median size retrievals. The tuned regressions with changeable values of the exponent b give slightly better results (18–23% in terms of RSD) compared with the tuned regression with b = const.

Figure 9 illustrates retrievals of vertical profiles of particle median size, D_m. This example is given for the same vertical profile of radar reflectivity measurements as in Figure 8. One can see that the tuned regression approach provides a quite good approximation of the reference profile of cloud particle median sizes obtained from the full radar–radiometer method. The RSD value between results of the tuned regression estimates and the full-method data for this observational case is 14%. The greatest disagreement (percentage-wise) is observed near the cloud top, where IWC is underestimated and D_m is overestimated. Note that when IWC is underestimated, D_m is usually overestimated and vice versa.

The better estimated accuracy of median size retrievals compared with that of IWC with the tuned regression approach can be explained, in part, by the fact that the exponent for D_m in (1) is greater than that for IWC. It results in smaller variations of reflectivity due to changes in IWC than due to changes in D_m of comparable relative magnitude. Hence the same changes in reflectivity are caused by smaller changes in median size than in IWC. Note that the comparisons of the retrieval results of the "full" method with collocated in situ observations also indicated a better agreement for particle median sizes than for IWC.

6. Sensitivity of Tuned Regression Retrievals to Variations of Particle Shape and PSD Width

The accuracies of the tuned regression approach were estimated in sections 4 and 5 using the same set of a priori assumptions about the particle shape parameter r and the order of the gamma function PSD, n, which is responsible for the PSD width, for both the full and the tuned regression methods. As soon as these assumptions are kept the same, the differences between the methods are practically the same for reasonable ranges of variability in n ($0 \le n \le 2$) and r ($0.3 \le r \le 1$). Changes in these assumptions, however, result in variations of the retrieval results.

Assumptions about n and r influence the values of IWC retrieved using the tuned regression method because the value of IWP in (5) obtained from the layer-mean radar reflectivity and an IR estimate of the cloud optical thickness depends on those assumptions. The variability of D_m due to assumptions is twofold: first, through IWP as for IWC retrievals, and second, through the dependence of the parameter G on n and r in (1).

The latter variability is expected to be quite modest, however, since $D_m \sim G^{1/3}$.

Sensitivities to the discussed a priori assumptions were analyzed by comparing tuned regression retrieval results for different assumed values of n and r relative to the results obtained for spherical particles ($r = 1$) and the first-order gamma function PSD ($n = 1$). The analysis showed that the changes in the assumed values of n from 1 to 0 and from 1 to 2 cause only slight variations in the retrieved values of IWC and D_m. The corresponding relative standard deviations are only 3% (for IWC) and 7% (for D_m) for the former case and 6% (for IWC) and 7% (for D_m) for the latter case, respectively, if all the ice cloud observations mentioned in Figure 4 are considered.

The sensitivity of the retrievals to the assumption of the particle shape parameter is somewhat greater. It is about 15% (for IWC) and 12% (for D_m) if r is changed from 1 to 0.5 for oblate (i.e., plate-type) particles and 10% (for IWC) and 8% (for D_m) for the same change in r for prolate (i.e., columnar-type) particles. Note that in the case of nonspherical particles, the median sizes D_m are still expressed in terms of diameters of the equal-volume spheres. The performed sensitivity tests indicate that variations of the retrieved cloud microphysical parameters due to changes in the a priori assumptions about gamma-function PSD width and particle aspect ratio are usually small compared with uncertainties of the tuned regression approach given in Tables 1 and 2.

7. Summary

The increasing role of millimeter-wavelength radars for cloud research requires efficient methods for microphysical retrievals which can be used in a "real time" mode and are applicable to the wide range of cloud conditions. Traditional power law regressions, which are akin to reflectivity–rain rate relations in radar meteorology, relate radar reflectivity Z_e to radiatively important cloud parameters such as ice water content and particle characteristic size. They are very convenient to use for the routine processing of radar data. However, they generally do not provide the necessary retrieval accuracy because of the large variability in their parameters. These parameters are usually established from individual case studies and change from one observational case to another. Estimates of IWC using different existing regressions for the same value of radar reflectivity can differ by as much as 1 order of magnitude.

The "tuned" regression approach suggested in this paper for retrieving vertical profiles of ice cloud microphysics offers a significant improvement in retrieval accuracy compared with traditional regressions. With this approach, the coefficient of the power law Z_e-IWC regression is adjusted for each vertical profile of radar data using simultaneous estimates of cloud optical thickness. Values of optical thickness and layer-mean radar reflectivity are used to obtain cloud ice water path, which, in turn, is used to normalize individual Z_e-IWC regressions for each vertical profile of radar data. In a simple case, vertically pointed IR measurements can be used for estimates of cloud optical thickness. However, any independent ground- or satellite-based estimates of optical thickness will suffice because visible and IR optical thicknesses of ice clouds are rather close for typical characteristic sizes of cloud particles [*Matrosov et al.*, 1998]. In case of satellite measurements, though, a problem of matching resolution volumes of different instruments is much more complicated than for the vertically pointed ground-based instruments. Once a vertical profile of IWC is retrieved using the tuned regression approach, cloud particle median sizes D_m at each radar range gate are calculated using the relation between radar reflectivity, IWC, and D_m (equation (1)).

The accuracy of the tuned regression approach was estimated by comparing its retrieval results with microphysical data obtained with the full radar–radiometer method. This method uses measurements of Doppler velocities in addition to radar reflectivity and IR measurements and was shown to provide good retrieval accuracies by comparisons of cloud parameters measured remotely and in situ [*Matrosov et al.*, 1998]. The use of Doppler information, however, requires conditions of relatively steady cloud with no significant updrafts/downdrafts and turbulence observed over a period of several hours. The procedure of using Doppler information for estimating cloud particle fall velocities [*Orr and Kropfli*, 1999] requires a posterior) processing of this information, thereby preventing the real-time use of this method.

Accuracy comparisons between the tuned regression approach and the full radar–radiometer method were performed for 12 observational ice cloud cases with more than 140,000 remote cloud samples. These cloud cases, which were observed with the ground-based, vertically pointed Ka-band radar and a narrowband Barnes type IR radiometer ($\lambda \sim 10$–11.4 μm) during various field programs in different geographical locations, satisfied conditions for the applicability of the full radar–radiometer method.

These comparisons showed that tuned Z_e-IWC regressions with a constant value of the exponent $b = 0.65$ provide significantly better accuracy than any a priori–chosen regression with fixed parameters. Further improvement of the accuracy is achieved by the assumption that b changes linearly from the cloud top to the cloud base, from about 0.6 to 0.7, which accounts for the typical larger variability of cloud particle sizes in the upper cloud parts. The relative standard deviations of the results obtained with the tuned regression approach are about 35% and 20% for IWC and particle median size compared with the retrievals with the full-radar radiometer method that uses additional Doppler information to get independent estimates of particle characteristic size. These accuracies should be considered quite satisfactory given the very high natural variability of ice cloud microphysics.

Acknowledgments. This research was funded, in part, through the NASA EOS Validation Program (D. O'C. Starr is Program Manager) and by the NOAA Office of Global Programs. The author is grateful to D. Atlas for helpful comments on this research.

References

Atlas, D., S. Y. Matrosov, A. J. Heymsfield, M. D. Chou, and D. B. Wolff, Radar and radiation properties of ice clouds, *J. Appl. Meteorol.*, *34*, 2329–2345, 1995.

Brown, P. R. A., and P. N. Francis, Improved measurements of the ice water content in cirrus using a total-water probe, *J. Atmos. Oceanic Technol.*, *12*, 410–414, 1995.

Brown, P. R. A., A. J. Illingworth, A. J. Heymsfield, G. M. McFarquhar, K. A. Browning, and M. Gosset, The role of spaceborne millimeter-wave radar in the global monitoring of ice cloud, *J. Appl. Meteorol.*, *34*, 2346–2366, 1995.

Clothiaux, E. E., M. A. Miller, B. A. Albrecht, T. P. Ackerman, J. Verlinde, D. M. Babb, R. M. Peters, and W. Syrett, An evaluation of a 94 GHz radar for remote sensing of cloud properties, *J. Atmos. Ocean. Technol.*, *12*, 210–229, 1995.

Dowling, D. R., and L. F. Radke, A summary of the physical properties of cirrus clouds, *J. Appl. Meteorol.*, *29*, 970–987, 1990.

Evans, K. F., and G. L. Stephens, Microwave radiative transfer through clouds composed of realistically shaped ice crystals, II, Remote sensing of ice clouds, *J. Atmos. Sci.*, *52*, 2058–2072, 1995.

Frisch, S. A., G. Feingold, C. W. Fairall, T. Uttal, and J. B. Snider, On cloud radar and microwave radiometer measurements of stratus cloud liquid water profiles, *J. Geophys. Res.*, *103*, 23,195–23,197, 1998.

Galloway, J., A. Pazmany, J. Mead, R. E. McIntosh, D. Leon, J. French, R. Kelly, and G. Vali, Detection of ice hydrometer alignment using an airborne W-band polarimetric radar, *J. Atmos. Oceanic Technol.*, *14*, 3–12, 1997.

Han, Q., R. Welch, and J. Chou, Retrieval of cirrus microphysics over oceans on a near-global scale, in *Proceedings of the AMS Conference on Cloud Physics*, pp. 583–585, Am. Meteorol. Soc., Boston, Mass., 1995.

Heymsfield, A., Ice crystal terminal velocities, *J. Atmos. Sci.*, *29*, 1348–1357, 1972.

International GEWEX Project Office, Utility and feasibility of cloud profiling radar, report of the GEWEX Topical Workshop N 10, *IGPO Publ. Ser. WMO/TD 593, WCRP-84,* 92 pp., World Meteorol. Org., Geneva, Switzerland, 1994.

Intrieri, J. M., G. L. Stephens, W. L. Eberhard, and T. Uttal, A method for determining cirrus cloud particle sizes using lidar and radar backscatter technique, *J. Appl. Meteorol.*, *32*, 1074–1082, 1993.

Inrieri, J. M., W. L. Eberhard, T. Uttal, J. A. Shaw, J. B. Snider, Y. Han, B. W. Orr, and S. Y. Matrosov, Multiwavelength observations of a developing cloud system: The FIRE II 26 November 1991 case study, *J. Atmos. Sci.*, *52*, 4079–4093, 1995.

Kosarev, A. L., amd I. P. Mazin, An empirical model of the physical structure of upper layer clouds, *Atmos. Res.*, *26*, 213–228, 1991.

Kropfli, R. A., and R. D. Kelly, Meteorological research applications of mm-wave radar, *Meteorol. Atmos. Phys.*, *59*, 105–121, 1996.

Kropfli, R. A., S. Y. Matrosov, T. Uttal, B. W. Orr, A. S. Frisch, K. A. Clark, B. W. Bartram, R. F. Reinking, J. B. Snider, and B. E. Martner, Cloud physics studies with 8-mm wavelength radar, *Atmos. Res.*, *35*, 299–313, 1995.

Liao, L., and K. Sassen, Investigation of relationships between Ka-band radar reflectivity and ice and liquid water content, *Atmos. Res.*, *34*, 231–248, 1994.

Mace, G. G., T. P. Ackerman, E. E. Clothiaux, and B. A. Albrecht, A study of composite cirrus morphology using data from a 94-GHz radar and correlations with temperature and large-scale vertical motion, *J. Geophys. Res.*, *102*, 13,581–13,593, 1997.

Mace, G. G., T. P. Ackerman, P. Minnis, and D. F. Young, Cirrus layer microphysical properties derived from surface-based millimeter radar and infrared interferometer data, *J. Geophys. Res.*, *103*, 23,207–23,216, 1998.

Matrosov, S. Y., Variability of microphysical parameters in high-altitude ice clouds: Results of the remote sensing method, *J. Appl. Meteorol.*, *36*, 633–648, 1997.

Matrosov, S. Y., T. Uttal, J. B. Snider, and R. A. Kropfli, Estimation of ice cloud parameters from ground-based infrared radiometer and radar measurements, *J. Geophys. Res.*, *97*, 11,567–11,574, 1992.

Matrosov, S. Y., B. W. Orr, R. A. Kropfli, and J. B. Snider, Retrievals of vertical profiles of cirrus cloud microphysical parameters from Doppler radar and infrared radiometer measurements, *J. Appl. Meteorol.*, *33*, 617–626, 1994.

Matrosov, S. Y., A. J. Heymsfield, J. M. Intrieri, B. W. Orr, and J. B. Snider, Ground-based remote sensing of cloud particle sizes during the 26 November 1991 FIRE II cirrus case: Comparisons with in situ data, *J. Atmos. Sci.*, *52*, 4128–4142, 1995.

Matrosov, S. Y., A. J. Heymsfield, R. A. Kropfli, B. E. Martner, R. F. Reinking, J. B. Snider, P. Piironen, and E. W. Eloranta, Comparisons of ice cloud parameters obtained by combined remote sensor retrievals and direct methods, *J. Atmos. Ocean. Technol.*, *15*, 184–196, 1998.

Minnins, P., D. P. Kratz, J. A. Coakley Jr., M. D. King, R. Arduini, D. P. Garber, P. W. Heck, S. Mayor, W. L. Smith Jr., and D. F. Young, Cloud optical property retrieval (subsystem 4.3), Clouds and the Earth's radiant energy system (CERES) algorithm theoretical basis document, vol. III, Cloud analysis and radiance inversions (subsystem 4), *NASA RP 1376*, *3*, 135–176, 1995.

Moran, K. P., B. E. Martner, M. J. Post, R. A. Kropfli, D. C. Welsh, and K. B. Widener, An unattended cloud-profiling radar for use in climate research, *Bull. Am. Meteorol. Soc.*, *79*, 443–455, 1998.

Orr, B. W., and R. A. Kropfli, A method for estimating particle fall velocities from vertically pointing Doppler radar, *J. Atmos. Oceanic Technol.*, *16*, 29–37, 1999.

Ou, S. C., K. N. Liou, and T. R. Caudill, Remote sounding of multilayer cirrus cloud systems using AVHRR data collected during FIRE-II-IFO, *J. Appl. Meteorol.*, *37*, 241–254, 1998.

Platt, C. M. R., and A. C. Dilley, Remote sounding of high clouds, IV, Observed temperature variations in cirrus optical properties, *J. Atmos. Sci.*, *38*, 1069–1082, 1981.

Ramanathan, V., and W. Collins, Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño, *Nature*, *351*, 27–32, 1991.

Sassen, K., and V. I. Khvorostyanov, Radar probing of cirrus and contrails: Insights from 2-D model simulations, *Geophys. Res. Lett.*, *25*, 975–978, 1998.

Sassen, K., and L. Liao, Estimation of cloud content by W-band radar, *J. Appl. Meteorol.*, *35*, 2705–2706, 1996.

Sekelsky, S. M., and R. E. McIntosh, Cloud observations with polarimetric 33 GHz and 95 GHz radar, *Meteorol. Atmos. Phys.*, *59*, 123–140, 1996.

Sekelsky, S. M., W. L. Ecklund, J. M. Firda, K. S. Gage, and R. E. McIntosh, Particle size estimation in ice-phase clouds using multifrequency radar reflectivity measurements at 95, 33 and 2.8 GHz, *J. Appl. Meteorol.*, *38*, 5–28, 1999.

Stephens, G. L., S.-C. Tsay, P. W. Stackhouse, and P. J. Flatau, The relevance of microphysical and radiative properties of cirrus clouds to climate and climate feedback, *J. Atmos. Sci.*, *47*, 1742–1753, 1990.

S. Y. Matrosov, R/E/ET6, 325 Broadway, Boulder, CO 80303. (smatrosov@etl.noaa.gov)

(Received November 6, 1998; revised April 5, 1999; accepted April 16, 1999.)